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Key Points:

- Remote sensing of rapidly evolving river delta bathymetry is limited by turbid water
- UAVSAR images resolve the subaqueous channel network through variation in water surface roughness
- UAVSAR time series resolves small incipient channels and 700 m of channel network extension

Supporting Information:

- Supporting Information S1
- Data Set S1

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Airborne radar imaging of subaqueous channel evolution in Wax Lake Delta, Louisiana, USA

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Abstract Shallow coastal regions are among the fastest evolving landscapes but are notoriously difficult to measure with high spatiotemporal resolution. Using Uninhabited Aerial Vehicle Synthetic Aperture Radar (UAVSAR) data, we demonstrate that high signal-to-noise L band synthetic aperture radar (SAR) can reveal subaqueous channel networks at the distal ends of river deltas. Using 27 UAVSAR images collected between 2009 and 2015 from the Wax Lake Delta in coastal Louisiana, USA, we show that under normal tidal conditions, planform geometry of the distributary channel network is frequently resolved in the UAVSAR images, including ~700 m of seaward network extension over 5 years for one channel. UAVSAR also reveals regions of subaerial and subaqueous vegetation, streaklines of biogenic surfactants, and what appear to be small distributary channels aliased by the survey grid, all illustrating the value of fine resolution, low noise, L band SAR for mapping the nearshore subaqueous delta channel network.

1. Introduction

Modern Earth- and planetary-surface science relies heavily and digital elevation models (DEMs) to study mass and energy transfer in terrestrial [*Passalacqua et al.*, 2015], planetary [*Smith et al.*, 1999], and oceanographic [*Reece et al.*, 2013] environments. Such DEMs are generally out of date or not present in the shallow (0–3 m) subaqueous regions of the world's river deltas. The lack of data across subaqueous delta regions severely limits our ability to understand and predict the geomorphic and ecologic evolution of these societally important landforms, which are threatened by rising sea levels, subsidence and human modification [*Tessler et al.*, 2015]. As examples, land building [*Kim et al.*, 2009], storm surge propagation [*Hope et al.*, 2013], marsh succession [*Carle et al.*, 2015], and ship navigation are each sensitive to subtle changes in delta front bathymetry. The data scarcity is located on the delta front directly seaward of the emergent delta, where shallow depths and rapidly evolving bathymetry inhibit boat-based surveys, and turbid waters prevent remotely sensed water-penetrating lidar or multispectral techniques. Hence, new methods for imaging across the subaqueous delta front are needed to better understand and develop solutions for the long-term sustainability of river deltas.

Presently, the most reliable measurement technique for delta front topography is single-beam acoustic sounding from small boats which provides limited sampling at best and requires significant spatial interpolation between track lines to build a DEM. *Alpers et al.* [2004] note that in 1995 between 0.8 and 1 billion U.S. dollars were spent worldwide to map shallow coastal bathymetry. Despite this investment, the measurements in coastal zones outside of established shipping lanes are significantly out of date or nonexistent. The site of this study, Atchafalaya Bay (Figure 1A), received its last full survey between 1900 and 1940, and these measurements are still used on official navigation charts [*NOAA*, 2015a]. Since this survey, the Wax Lake Delta has prograded ~10 km into Atchafalaya Bay. This delta is being studied carefully as examples of natural sediment diversions building new land in coastal Louisiana [*Paola et al.*, 2011].

Remote sensing techniques have the potential to map Earth's shallowly submerged landscapes at high spatial and temporal resolution. However, multispectral and bathymetric lidar techniques that have been developed for shallow coastal regions rely on relatively clear water [*Klemas*, 2013] and are unsuccessful around river deltas where fine-grained sediment transported as wash load produces turbid waters. Backscattered microwave radiation from synthetic aperture radar (SAR) is sensitive to shallow bathymetry indirectly where currents, affected by bottom topography, alter the water surface roughness [*Alpers and Hennings*, 1984; *Alpers et al.*, 2004]. SAR can potentially resolve uneven bathymetry in turbid environments and has been used to detect

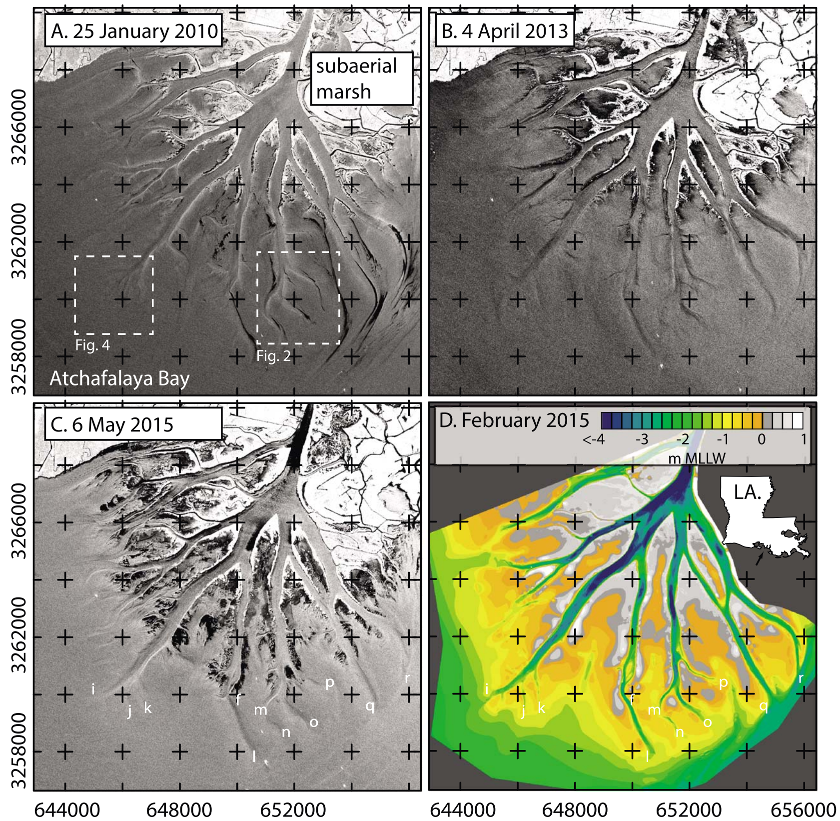

Figure 1. Comparison of bathymetry and UAVSAR imagery of the Wax Lake Delta. Crosses are separated by 2 km. Coordinates are universal time meridian (UTM) zone 15 N. (a–c) UAVSAR images from 15 January 2010, 4 April 2013, and 6 May 2015 (Supplementary Table S1). Subaerial marsh and the locations of Figures 2 and 4 are shown on Figure 1a. (d) Bathymetric survey collected in February 2015. Elevations are referenced to mean lower low water (MLLW). Inset map of Louisiana shows general site location. Features that are found in both Figures 1c and 1d are marked with white letters.

large shallow marine sand banks [*Fu and Holt*, 1982; *Hennings*, 1998] and tidal bar features [*Vogelzang*, 1997]. However, SAR has not yet been extended to monitor the complex and rapidly evolving channel networks at the delta front—a data gap we address here.

In this study, we demonstrate that airborne SAR images from the Uninhabited Aerial Vehicle Synthetic Aperture Radar (UAVSAR) can produce detailed maps of the subaqueous distributary channel network that can equal or exceed the sensitivity of field surveys and that the growth of the channel network can be tracked in time with repeated SAR imaging. We focus the study at the Wax Lake Delta, Louisiana, because of its recent time series of bathymetric DEMs dating back to 2010 [*Shaw and Mohrig*, 2014] and frequent imaging by UAVSAR since 2009 (supporting information Table S1). These data provide a rare opportunity to ground truth the airborne radar imagery. In this proof-of-concept study, we demonstrate the potential broad utility of airborne SAR in partially filling the data gap that exists in shallowly submerged regions of river deltas worldwide and provides a tractable means to monitor delta front planform evolution through repeat surveys.

2. Study Location: Wax Lake Delta, Louisiana

The Wax Lake Delta (WLD) is a river delta prograding into Atchafalaya Bay in coastal Louisiana (Figure 1). The delta is fed from the Atchafalaya River through the Wax Lake Outlet, a flood control channel dredged in 1942. The delta initially formed in 1973 [*Roberts et al.*, 1980] when river-transported sand first reached Atchafalaya Bay. Since then, the delta has built 70 km^2 of land that is subaerially emergent at low tide [*Allen et al.*, 2012]. Bathymetric surveys of the delta front beyond the emergent delta show that the total area of deltaic deposition (132 km^2) is far larger than the emergent delta (Figure 1d). Distributary channels extend several kilometers into the delta front and are deep compared to the surrounding interdistributary bays (Figure 1d). *Shaw and Mohrig*

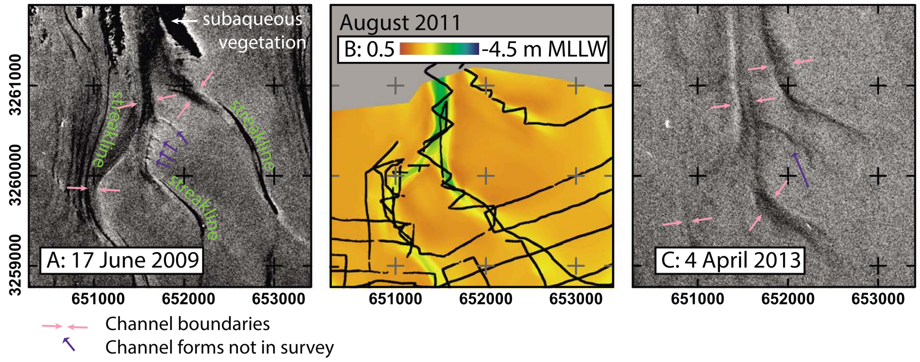

Figure 2. Interpretation of UAVSAR images at Greg Pass (see Figure 1 for location). Crosses are separated by 1 km. (a) UAVSAR image from 17 June 2009 showing signatures of exposed mudflats or subaqueous near-surface marsh vegetation, streaklines on the water surface, channel boundaries between the pink arrows, and channel forms that are not found on surveyed bathymetry (purple arrows). (b) Bathymetry collected in August 2011. Black lines show boat path during the survey. Elevations are shown relative to mean lower low water (MLLW). (c) UAVSAR image 4 April 2013. Note that channel boundaries are more diffuse than in Figure 2a, probably due to a decrease in UAVSAR transmitted power, as discussed in the text.

[2014] conducted repeat boat-based sonar surveys of the delta front near one of the main distributaries of the Wax Lake Delta and found the channel network to be evolving rapidly through channel extension during periods of low river discharge and through network planform evolution during high river discharge. Airborne bathymetric lidar surveys of the delta, attempted in 2013, were unsuccessful in resolving these features because the perennially turbid water limited light penetration to a few decimeters. These conditions are common on river deltas worldwide and highlight the need for new methodology.

3. Methods

3.1. Bathymetric Surveys

Four boat-based bathymetric surveys are used for validating UAVSAR interpretations. Surveys obtained in July 2010, August 2011, and February 2012 were presented previously by *Shaw and Mohrig* [2014]. A new survey was added to this series in February 2015. In all cases, surveys were performed using one to four georeferenced single-beam sonar units mounted to a shallow-draft boat. The surveys cover areas where water depth was sufficient to allow passage of the vessel ($>$0.3 m). In deep unchannelized regions, measurements were collected on a ~200 m survey grid. In distributary channels where channel margins were too shallow to cross with the boat, surveys were necessarily limited to within the channel itself (Figure 2b) [supporting information]. Water depth measurements were filtered of any soundings interpreted to be spurious by nearest neighbor comparisons. The processed data were then concatenated with tide gauge measurements at Amerada Pass [*NOAA*, 2015b] to determine the bed elevation referenced to mean lower low water (MLLW), which is 0.26 m below mean sea level in Atchafalaya Bay.

The elevation data along the survey lines were used to build DEMs of the delta front. Contours were drawn at 0.2 m depth intervals across the delta front, and the DEM was interpolated from these contours. DEMs have a vertical root-mean-square error of ~0.1 m when compared to the sounding points. For the February 2015 survey, the delta front DEM was combined with airborne laser altimetry flown in February 2013 and multibeam sonar data collected in the deeper delta channels upstream of the delta front collected in 2007, 2009, and 2013 to produce the most complete DEM of the Wax Lake Delta to date (Figure 1d; available in the supporting information).

3.2. UAVSAR

Airborne UAVSAR is a 1.257 GHz (L band) SAR operated by the U.S. National Aeronautics and Space Administration (NASA) that has high spatial resolution (~7 m in standard products) and a low instrument noise floor [*Fore* et al., 2015], making it well suited for imaging oceanographic features for which the radar backscattered signal is small. Furthermore, SAR can image water or land through clouds and without sunlight, which are limiting factors for optical remote sensing in many coastal environments. UAVSAR imaged the

Wax Lake Delta 27 times between June 2009 and May 2015 (supporting information Table S1). For each image, we report in supporting information Table S1 the river discharge to the delta (Q_w) measured at Calumet, LA (U.S. Geological Survey (USGS) gauge #07381590), and tidal height (*H*) and wind conditions, measured at the Amerada Pass tide gauge in Atchafalaya Bay (NOAA gauge #8764227), located ~9 km southeast of the Wax Lake Delta.

This study uses UAVSAR data acquired in the VV mode (vertical transmit polarization and vertical receive polarization) that are available as standard multilooked and georeferenced "grd" products. In areas of low roughness, as from calm water, the measured return signal from open water can be below the instrument noise floor. In April 2011, the noise floor of the UAVSAR instrument increased by 5 dB [*Fore* et al., 2015], so the images after this date show a reduced contrast between bright and dark features in the water. The backscattered signal from open water depends strongly on the meteorological conditions, particularly wind speed, which accounts for variations in image intensity across the data set.

In this study, UAVSAR images were compared with sonar-based DEMs (i) to determine the signatures of bathymetry as well as biogenic surfactants and vegetation visible in UAVSAR images, (ii) to determine the environmental conditions where UAVSAR resolves the subaqueous channel network, and (iii) to assess whether UAVSAR is capable of capturing channel network growth. In most cases, comparisons were made between DEMs and UAVSAR images collected less than 6 months apart. *Shaw and Mohrig* [2014] found that channels could extend by up to 500 m over similar time intervals. However, we will show that DEMs were directly comparable to networks mapped from UAVSAR imagery.

4. Results

The WLD is well resolved using UAVSAR, as shown in Figure 1. We interpret four backscatter signatures observed throughout the UAVSAR image series. On the subaerially emergent delta we find (1) subaerial and (2) subaqueous vegetation signatures, and on the delta front we observe (3) surface films passively flowing across the delta, and (4) variations in the image intensity associated with bathymetry.

Subaerially exposed marsh vegetation along island margins produces strong backscatter of the incident radar pulses and is typically the highest intensity regions on the SAR image (bright regions, Figures 1a–1c). Subaerial vegetation is focused at topographic highs along channel levees where trees grow up to ~10 m high [*Johnson et al*., 1985; *Shaw et al*., 2013]. Low backscatter regions (dark regions, Figures 1 and 2a) found in island interiors or further seaward along channel levees are identified as regions of submerged aquatic vegetation, consistent with surveys and remote sensing presented by *Carle et al*. [2015]. Submerged aquatic vegetation suppresses surface waves producing regions with the lowest backscattered radar returns on the delta. We note, however, that very shallow or subaerially exposed mud and sand flats devoid of vegetation could also produce this low backscatter intensity signature.

On the delta front, dark curvilinear bands several kilometers long are interpreted to be the signature of biogenic surfactants or slicks on the water surface (Figure 2a) [*Alpers and Hühnerfuss*, 1989; *Hühnerfuss et al*., 1994]. The viscoelastic properties of these surface films suppress the formation of short waves and therefore reduce backscatter [e.g., *Hühnerfuss et al*., 1994; *Gade et al*., 1998]. These features are termed streaklines because they are passive flow tracers that appear to emanate from localized sources [*Kundu et al*., 2011]. Streaklines on the Wax Lake Delta are resolved in near-infrared imagery as well as radar [*Shaw et al*., 2016]. Because they damp the surface waves so strongly, streaklines are the primary signal obscuring bathymetric imaging on the Wax Lake Delta.

Streaklines composed of biogenic slicks occur when winds are low. Previous studies have found biogenic slicks to be mixed away when winds exceed 6–10 m/s [*Espedal et al*., 1996; *Alpers and Espedal*, 2004]. Investigation of the UAVSAR series for the WLD (supporting information Table S1) shows that streaklines are only present when winds are less than about 2.5 m/s. The time series of 12 images acquired on 8 May 2015, ~20 min apart show a fading of the streaklines in the imagery as wind velocity increases from about 1.5 to 3 m/s (supporting information Table S1).

The bathymetric signature in the SAR data, the primary focus of this study, can be seen in the areas where channels extend into the subaqueous delta front basinward of the subaerially exposed delta (Figures 1 and 2). SAR does not detect the channel bottom directly, i.e., the radar pulses do not penetrate through the water to

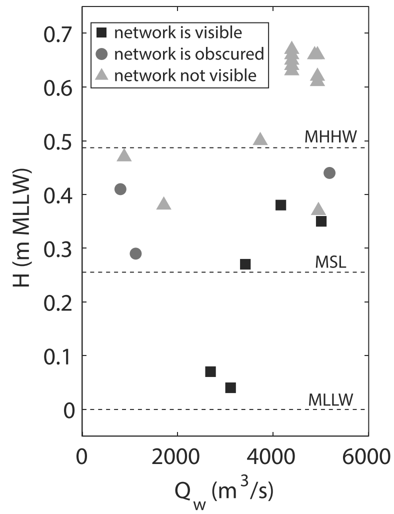

Figure 3. Plot showing the presence or absence of channel network signatures in UAVSAR imagery as a function of water discharge to the delta Q_w and tidal elevation H (supporting information Table S1). Black squares mark conditions where the entire channel network is clearly visible. Dark gray circles mark conditions where most of the channel network is traceable, but some regions are unclear. Light gray triangles mark conditions where the subaqueous channel network is not discernible. Dotted lines are drawn at mean lower low water (MLLW), mean sea level (MSL), and mean higher high water (MHHW).

scatter from the bottom surface, but rather detects backscatter changes induced by changes in the water surface shortwave spectrum in areas of different current velocity over uneven bathymetry [*Alpers and Hennings*, 1984]. The bathymetric signature is a variation in image intensity between channelized and unchannelized areas.

In some circumstances, depending on the relative orientation of the channels with respect to the SAR viewing direction, a single channel can appear bright on one channel margin and dark on the opposite channel margin. This is the result of a Doppler shift effect known as velocity bunching, where moving objects on the surface modulate the image intensity dependent on their velocity component in line with the SAR imagining direction [*Alpers and Hennings*, 1984]. Velocity bunching signatures were never more than 50 m from the submerged channel and were frequently separated by less than 10 m. We can make use of this important scattering signature to more clearly identify a channel, including with multiple images (e.g., Figure 1c, with channel ending at i, j, and k, and Figure 2a).

The UAVSAR series of the WLD displays bathymetric signatures with varying clarity. By comparing bathymetric surveys to the UAVSAR imagery, we were able to evaluate visually whether bathymetry was traceable, and the results are summarized in supporting information Table S1. Because this procedure is subjective, instances where the bathymetric signature is partly obscured are indicated in the supplementary table as well. We analyzed their occurrences with respect to tidal level (H) and river discharge (Q_w) at the time of the acquisitions (Figure 3). The bathymetric signature is observed or partially observed for all five images where $H < 0.35$ m MLLW and in 8 of the 11 images where H was less than mean higher high water (MHHW: 0.49 m MLLW). The bathymetric signature was not observed for any image collected when $H >$ MHHW (Figure 3). The radar signature is visible on UAVSAR imagery when the tide is low, but it is frequently visible in normal tidal conditions between MLLW and MHHW. Although it was expected that flood stage water discharge (~5000 m^3/s) would increase velocity gradients and therefore network visibility on UAVSAR images, such a trend was not apparent in Figure 3.

UAVSAR resolves each subaqueous channel mapped in February 2015 from the large, persistent bifurcations found on Gadwall and Greg Passes (Figure 1 locations i, j, k, m, n, o, and p). Interestingly, the UAVSAR image also shows channel-like signatures in regions not surveyed by boat (Figure 2). In June 2009, there were four such signatures spaced at ~ 200 m intervals on Greg Pass ranging from 80 to 100 m in length (Figure 2a). In April 2013, only the longest of the previous four signatures was unequivocally present and it had extended to 500 m in length. Bathymetry was not surveyed in these regions due to the shallowness of the surrounding channel margins (Figure 2b). Since there is no record of these shapes in the bathymetric data, they are not present in the interpolated DEM.

The evolution of the channel network can be tracked using UAVSAR. Figure 4 compares three bathymetric surveys of Gadwall Pass to UAVSAR images. In July 2010 (Figure 4a), the four distributary channels were of roughly equal length and width. The UAVSAR image shows the width and extent of each of these features (Figure 4b). Between July 2010 and February 2012, the delta front evolved considerably due to tidally mediated sediment transport during periods of low river flow and significant evolution during the historic flood of 2011 [*Shaw and Mohrig*, 2014]. UAVSAR image from 07 February 2012 reflects this change in morphology. The channel marked "n" (Figure 4c)

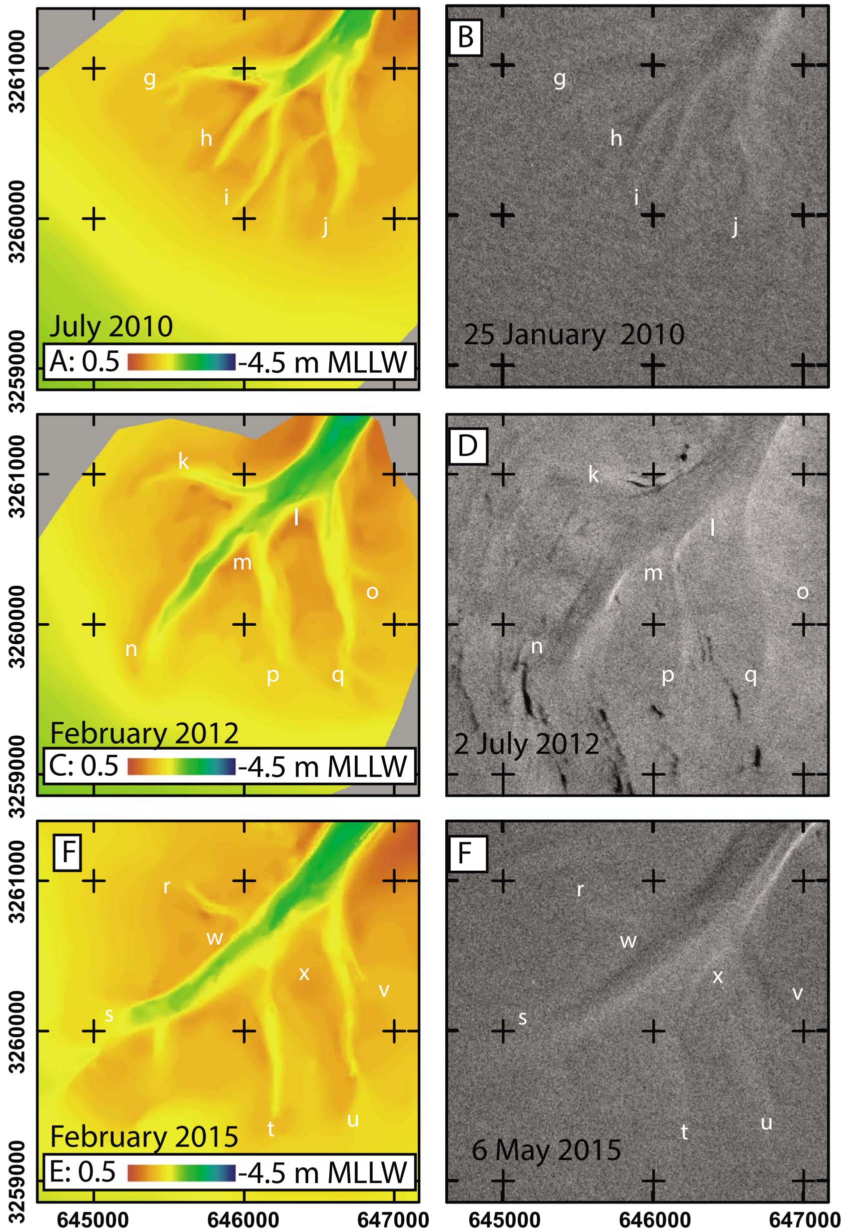

Figure 4. Detailed map of Gadwall Pass (see Figure 1a for location) comparing the evolution of (a, c, and e) to the surveyed channel network to (b, d, and f) the UAVSAR images. Crosses are separated by 1 km. Corresponding features found in both DEM and UAVSAR image are marked with white letters.

extended and widened significantly. The other three channels (k, p, and q) narrowed and rearranged to branch off of channel "n" rather than existing as symmetric bifurcations. Furthermore, the downstream migration of the subaqueous shoals separating channels noted by *Shaw and Mohrig* [2014] is also clear at locations "l" and "m" (Figure 4c). Each of these changes to the delta front bathymetry are resolved in the 2 July 2012, UAVSAR image (Figure 4d). Between February 2012 and February 2015, channel "s" changed its shape from curving toward the south to curving toward the east (Figure 4e). The other three channels (locations r, t, and u) maintained their general flow direction and either extended basinward (location t) or retreated (location r). These changes are clearly visible in UAVSAR image 5 June 2015 (Figure 4f). Although there were several UAVSAR images that did not show a bathymetric signature, there were no cases of false positives, i.e., locations where the radar signature of a channel occurred where we could confirm that no channel existed. UAVSAR imagery accurately depicted the growth of the channel network over this period.

5. Discussion and Conclusions

We have shown that the subaqueous channel network of the Wax Lake Delta can be mapped remotely using fine spatial resolution, low noise, L band SAR, as demonstrated with UAVSAR. SAR is sensitive to water surface waves at the centimeter to decimeter scale, which are affected by variable water depths and flow patterns on the delta front. Distributary channels extend as well-defined bathymetric features kilometers beyond the shoreline, and their planform shape can be easily resolved by the fine resolution SAR. UAVSAR imagery also shows signatures of streaklines composed of biogenic slicks and regions of subaerial and subaqueous vegetation.

The 27 UAVSAR images available for the WLD provide variable clarity for mapping the subaqueous channel network. Channel network remote sensing is improved by imaging at low tide to obtain greater contrast between deep channels and shallow channel margins; however, most images collected in the normal tidal range (between MLLW and MHHW) also contain information about the subaqueous channel network. In contrast, streaklines of biogenic slicks on the water surface are more apparent during light winds when surfactants are less likely to be mixed by surface waves. Because streaklines appear to be a common feature, radar imaging when wind velocity exceeds 2.5 m/s could avoid this source of surface wave damping and improve the overall detection of delta bathymetry.

Using SAR to explicitly estimate local water depths and produce DEMs remains a difficult task. This inversion problem requires accurate modeling of the interaction of the current with the bottom topography, the effect of surface currents on the sea surface roughness, and the radar scattering from the ocean. Radar scattering depends on radar frequency, imaging geometry, and wind speed and direction [*Romeiser and Alpers*, 1997]. However, mapping the plan view channel network shape and its temporal and spatial evolution directly from SAR is a valuable tool that does not require complex modeling. The simple distinction between channels that are relatively deep and unchannelized areas that are relatively shallow may be sufficient information for the application of SAR to navigation, ecology, and delta morphodynamics.

UAVSAR can contribute new insight into delta channel network processes. Features that appear to be incipient channels are resolved in imagery but were not resolved in DEMs where grid-based mapping techniques were limited by shallow water depths outside of channels. This is the first time that such channels have been documented. Their transience may be a key aspect of channel initiation on the delta front. Field based research is clearly necessary to fully investigate these phenomena; however, UAVSAR has provided the means to observe them for the first time.

A brief survey of SAR databases shows that similar patterns exist on other river deltas, providing encouragement that similar methods could be used globally where boat-based DEMs are infrequent or nonexistent. A UAVSAR image of the Apalachicola Delta in NW Florida (supporting information Figure S1a) presents many of the same signatures as the WLD, revealing extensive streaklines and a subaqueous channel network extending 1 km seaward of the emergent delta. SAR imagery collected from satellites also shows many of the same signatures as discussed here. Supporting information Figure S1b shows Phased Array type L band SAR (PALSAR) from the ALOS-1 satellite for a portion of the Ganges-Brahmaputra delta, and many subaqueous channels can be delineated via velocity bunching. Bathymetric data are scarce for most of the world's deltas including the Apalachicola and Ganges-Brahmaputra, so SAR based study can have a high impact by revealing their channel network structure and evolution for the first time. Satellite-based SAR has been available for the past 25 years with almost global coverage. This database is an underutilized resource that may reveal decades of channel network evolution on the global delta population, as it has at the Wax Lake Delta.

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